Vol. 14, No. 4 (2025): 1335 - 1348 https://doi.org/10.23960/jtepl.v14i4.1335-1348

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Life Cycle Assessment of Organic Waste Pellet for Sustainable Energy Production in IPB University Campus

Sri Mulyani[2], Edy Hartulistiyoso[1,✉], Supriyanto[1]

[1] Department of Mechanical and Biosystem Engineering Faculty of Engineering and Technology IPB University, Bogor, INDONESIA.

[2] Nature Resource and Environmental Management Science, Graduate School, IPB University, Bogor, INDONESIA

Article History:

Received : 02 March2025
Revised : 16 Mach 2025
Accepted : 28 March 2025

Keywords:

Environmental impact,
GWP,
Life cycle assessment,
Pellet,
Renewable energy.

Corresponding Author:
✉ edyhartulistiyoso@apps.ipb.ac.id
(Edy Hartulistiyoso)

ABSTRACT

The growing population and improving living standards are resulting in higher demand for energy and materials. Renewable energy addresses this challenge while reducing greenhouse gas emissions. Organic waste has significant potential to be converted into pellet-based renewable energy, but sustainable production is essential to minimize environmental impact. This study aims to evaluate the environmental impact using a life cycle assessment with 5 categories, namely Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TAC), Freshwater Eutrophication (FEU), and Human Carcinogenic Toxicity (HCT) for each pellet. The results of twig and leaf pellets were, respectively, GWP of 3.05 kg CO_2-eq and 0.54 kg CO_2-eq; SOD of 1.6×10^{-6} kg CFC11 eq and 1.35×10^{-7} kg CFC11-eq; TAC of 0.0131 kg SO_2-eq and 0.0018 kg SO_2-eq; FEU of 0.0059 kg P-eq and 0.0006; HCT 0.538 kg 1.4-DCB-eq and 0.0130 kg 1.4-DCB-eq. Based on the result, the production of twig pellets has a higher environmental impact than that of leaf pellets. However, when compared to conventional fuels, the impact caused by twig pellets is still within acceptable limits and is comparatively lower.

1. INTRODUCTION

Energy consumption is closely linked to urbanization, modernization and industrialization. The energy sector accounts for 35% of global CO_2 emissions that have reached 37 billion metric tons (IPCC, 2014), while fossil fuels still supply 80% of global energy needs (IEA, 2024). For example, at IPB University energy use for laboratories, offices, and facilities is still largely dependent on conventional electricity. Large-scale use of fossil fuels increases emissions of gases such as SO_2, NO_2, and CO_2, which cause environmental problems (Farobie *et al*., 2022).

Dependence on conventional energy exacerbates environmental impacts (Martins *et al*., 2019). For the reduction of CO_2 emissions and mitigation global warming, a transition to carbon-neutral energy is essential (Saleem *et al*., 2022). Biomass, with its closed carbon cycle, presents a viable alternative (Çetinkaya *et al*., 2024). As an agriculture-based institution covering 267 hectares, IPB University generates substantial biomass waste, including twigs, leaves, and food scraps. Thus, it is responsible for implementing sustainable waste management to support environmentally sound development (Kumaat *et al*., 2023).

Based on DPSPLK IPB data in 2018, the IPB campus produces around 188 tons of organic waste per year, with the contribution of organic waste in the form of twigs and leaves reaching 75 tons per year. This potential could be utilized as a source of renewable energy to support the principle of sustainability in the campus environment. The type of renewable energy that can be produced is biopellets, which offer various environmental advantages in terms of transportation, use, and storage (Hernandez *et al*., 2019).

Evaluating the sustainability of pellet production through the Life Cycle Assessment (LCA) approach is a crucial step in meeting energy needs while mitigating environmental impacts to support the clean energy transition (Saosee *et al*., 2020). One of the main challenges in applying the LCA method is the process of collecting accurate and comprehensive data to support the inventory system (Siregar *et al*., 2020). Local data inventories often face limitations in accessing relevant datasets from available databases (Supriyanto *et al*., 2025).

Several studies have analyzed the environmental performance of pellet production from various biomass sources, including wood residues and forestry by-products (Ruiz *et al*., 2018). LCA-based assessments of pellet production's environmental impact have also increased in recent years (Sgarbossa *et al*., 2020). Additionally, research on greenhouse gas (GHG) emissions from pellet production indicates that biomass pellets, such as wood pellets, can significantly reduce GHG emissions compared to fossil fuels (Buchholz *et al*., 2017). These findings support the potential of organic waste pellets as a sustainable energy source with lower environmental impact.

This study aims to analyze and compare the environmental impacts of each stage of pellet production using the LCA approach with twigs and leaf raw materials. The results are expected to provide insights for sustainable organic waste management. The benefits include reducing waste volume, reducing greenhouse gas emissions, and producing environmentally friendly renewable energy.

IPB University has the potential to become a role model for other educational institutions in implementing a renewable energy-based waste management system. In addition, this research can be a medium of education and innovation for students, academic staff, and the general public, to introduce and implement sustainable and science-based environmental management practices.

2. MATERIALS AND METHODS

Data collection and research were conducted from August to November 2024 in the Bogor Agricultural University Campus Area, specifically at the Spirit Park IPB Landfill (TPA) and Lewikoppo Renewable Energy Laboratory, Department of Mechanical Engineering and Biosystems IPB, Dramaga District, Bogor Regency (Figure 1).

2.1. Goal and Scope

This research focused on the pellet production process based on organic waste in the IPB University Dramaga Campus area, which includes dry twig and leaf waste as presented in Figure 2. The pellet production process included the transportation of raw materials from various organic waste collection locations in the IPB area, the raw material preparation process, and the palletization stage followed by drying the pellets.

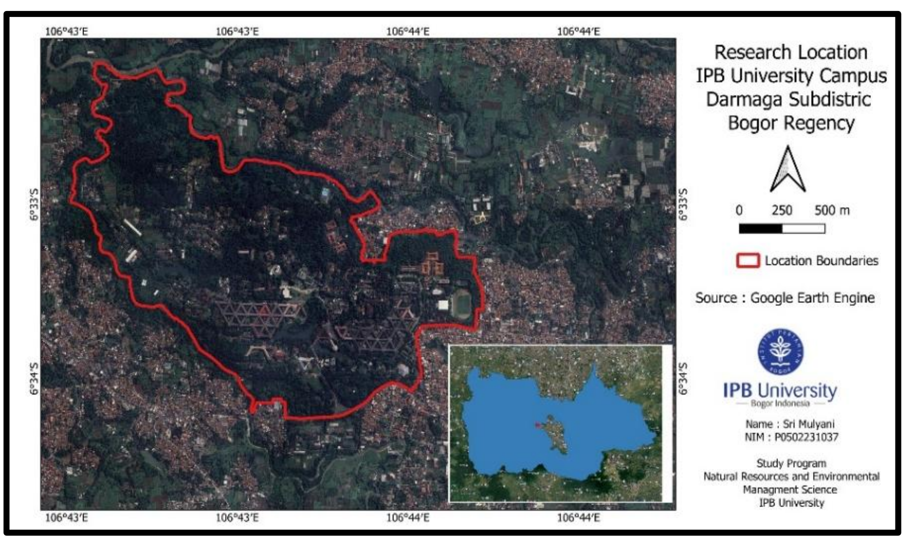


Figure 1. The overall location of the study

Figure 2. Twig and leaves that potentially can be explored as feedstock for pellet production

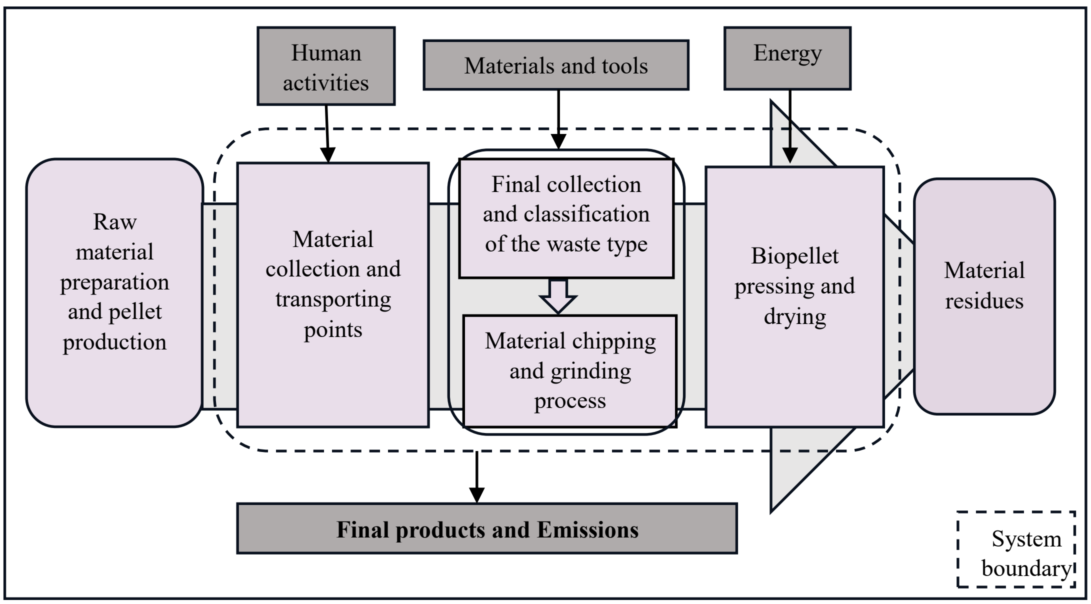


Figure 3. System boundaries of organic waste-based pellet production

Life cycle inventory data was collected from the IPB Spirit Park landfill and the Department of Mechanical and Biosystem Engineering's Renewable Energy Laboratory, using the cradle-to-gate boundary as illustrated in Figure 3. The scope of this research was chosen to evaluate the extent to which organic waste-based pellet production in the IPB area contributes to environmental impacts. The results of this study are expected to be implemented in a sustainable organic waste management strategy and have the potential as an environmentally friendly alternative energy source while reducing the accumulation of organic waste in the IPB area. This study does not cover production processes such as the cultivation of the main raw materials and the distribution of pellets to consumers or direct utilization in industries because this distribution is carried out outside the IPB area.

2.2. Pelet Production

For a comprehensive and systematic understanding of the biopellet production process, the next section presents a flow chart that outlines the production stages sequentially in accordance with the system boundaries that have been established. The flow chart is designed to visualize the process flow in a structured manner, starting from raw materia preparation, densification process, to the final stage of production.

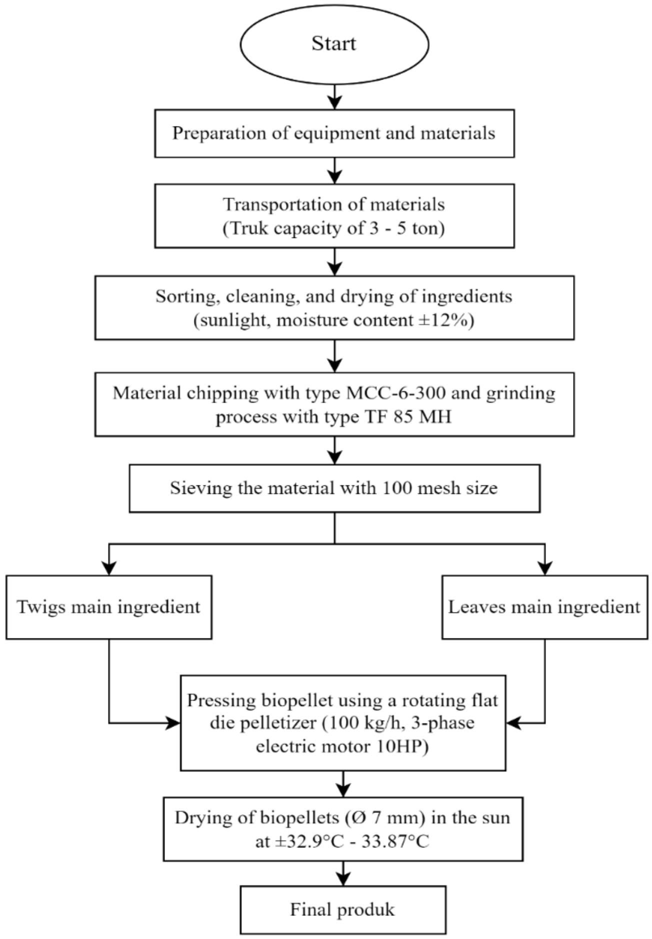


Figure 4. Biopellet production flow diagram

2.3. Life-Cycle Inventory

In this research, the inventory analysis stage aims to identify and collect inventory data covering inputs and outputs at each stage of the organic waste-based pellet production process at the IPB Campus (Figure 4). Inventory analysis was conducted using two approaches, namely primary data and secondary data. Primary data were obtained through direct measurements during the raw material preparation and production processes carried out at the Renewable Energy Laboratory and at Taman Semangat Landfill, as well as through interviews with management staff at the Landfill Semangat Park.

The secondary data was collected from a literature review related to the previous production of pellets from various types of materials. Data collection was carried out based on the objectives and limitations of the research that had been determined in the previous stages. Based on the flowchart presented in Figure 4, data collection starts from the process of transporting raw materials from all areas of the IPB Campus to the Landfill Spirit Park to the final stage of pellets production presented in Table 1.

2.4. Life Cycle Impact Assessment

The environmental impact of the organic waste-based pellet production process at the IPB campus was analyzed using SimaPro 9.5.0.2 software with the ReCiPe 2016 characterization method approach. This method was chosen as it is one of the most commonly used LCA analysis approaches, as it uses characterization factors from the IPCC report

Table 1. Inventory data quantification

Process stages	Process sub-stages	Inventory data	Unit
Raw materials distribution process		Diesel fuel	L
		Distance	km
Biopellet production	Drying and cleaning of twigs and leaves	Twigs	kg
		Leaves	kg
		Human labour	h
		Dry twigs	kg
		Water vapours	L
		Dry leaves	kg
		Water vapours	L
	Material chopping	Dry twigs	kg
		Human labour	h
		The electrical energy of the chopper machine	kWh
		Twig cuttings	kg
		Biomass waste	kg
	Material grinding	Twig cuttings	kg
		Human labour	h
		Diesel fuel	MJ
		Dry leaves	Kg
		Human labour	h
		Diesel fuel	MJ
		Twig trituration	kg
		Leaves trituration	kg
		Biomass waste	kg
	Biopellet pressing	Twig trituration	kg
		Human labour	h
		The electrical energy of the pelletizer machine	kWh
		Leaves trituration	kg
		Human labour	h
		Electrical energy	kWh
		Twig pellets	kg
		Leaves pellets	kg
	Drying of biopellets	Twig pellets before	kg
		Leaves pellets before	kg
		Drying duration	h
		Dry twig pellets	kg
		Water vapours	L
		Dry leaves pellets	kg
		Water vapours	L

with the most common methods (Martin-Gamboa *et al*., 2020), and it provides a range of universal characteristic factors that are relevant to the Indonesian context. The ReCiPe 2016 method produces characterization analysis in 18 impact categories, but this study only focuses on the 5 most relevant impact categories based on the PROPER regulation (KLHK RI, 2021) on mandatory environmental impact assessment. The impact categories analyzed included Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TAC), Freshwater Eutrophication (FEU) and Human Carcinogenic Toxicity (HCT).

This analysis is important because energy production from conventional sources, such as coal, has serious environmental impacts. Based on IPCC and Ecoinvent data (Table 2), every 1 kg of coal produced produces 2.3–2.8 kg of CO_2, depending on the type of coal. The process of producing and burning coal also emits SO_2 and NO_x, which

Tabel 2. Environmental impact comparison reference for conventional fuels

Fuels	Emission of CO_2 (kg CO_2-eq per unit)	Main Environmental Impacts
Coal	2.3–2.8 (per kg)	Particulate emissions, SO_2, NO_x, ecosystem degradation
Petroleum	3.0–3.2 (per liter)	Oil spill, GHG emissions, air pollution
Natural gas	1.9–2.3 (per m^3)	Methane emissions, NO_x
Diesel	2.7–3.1 (per liter)	Particulate emissions, NO_x, SO_2

Source: IPCC and Ecoinvent

emissions, which cause soil acidification and carcinogenic toxicity from fine particulates. In addition, coal mining often damages the ecosystem. By comparing the environmental impacts of organic pellets and coal, this study highlights the potential of organic pellets as a sustainable energy alternative.

2.5. Interpretation: The Final Stage of LCA

Life Cycle Assessment is a method for evaluating the environmental impacts of a product, process, or activity throughout its life cycle, from production to end-of-life. Interpretation is the final stage of LCA, which is an analysis involving data from the inventory analysis and impact assessment stages to identify opportunities to reduce the environmental impacts of the product system under study. Interpretation is a crucial stage in LCA analysis because it converts quantitative data from inventory analysis and impact assessment into significant insights. These insights can aid in decision-making and provide useful information for formulating sustainability strategies.

3. RESULTS AND DISCUSSION

3.1. Inventory analysis

The inventory analysis in the production of pellets based on organic waste from twigs and leaves includes data sources, a literature review, and an inventory that includes quantification of all input and output data in the production process. This study used 11 datasets consisting of 9 datasets as input (Table 3) and 2 datasets as output (Table 4), which were obtained from the SimaPro database. The data was used to compile an inventory classification at the twig and leaf pellets production stage.

In this inventory of twig and leaf pellets, there are 2 ID datasets (electrical energy in grinding and pelletization), 1 IN dataset (water), 1 FR dataset (biomass waste), 3 RoW datasets (transportation, small pieces of twigs, and twigs

Table 3. Input data sources

Input Data	Qty	Unit	Dataset	Database
Transportation	133.34	ton km	Transport, freight, lorry 3.5–7.5 metric ton, EURO3 {RoW}| market for transport, freight, lorry 3.5–7.5 metric ton, EURO3 | Cut-off, U	Ecoinvent 3
Forest residue products	32.5	kg	7 Forest products, EU27	EU & DK
Dry leaves	26.12	kg	Compost {GLO}| market for compost | Cut-off, U	Ecoinvent 3
Wood chips	31.15	kg	Wood chips, dry, measured as dry mass {RoW}| market for wood chips, dry, measured as dry mass | Cut-off, U	Ecoinvent 3
Twig trituration	21.16	kg	Sawdust, wet, measured as dry mass {RoW}| market for sawdust, wet, measured as dry mass	Ecoinvent 3
Water	9	L	Tap water {IN}| market for tap water | Cut-off, U	Ecoinvent 3
Chopping (electrical energy)	0.89	kWh	Electricity, low voltage {ID}| market for electricity, low voltage | Cut-off, U	Ecoinvent 3
Diesel fuel	75.24	MJ	Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	Ecoinvent 3
Pelletizer (electrical energy)	2.25	kWh	Electricity, high voltage {ID}| market for electricity, high voltage | Cut-off, U	Ecoinvent 3

RoW = Rest of World; GLO = Global; ID = Indonesia; EU & DK = Europa & Denmark; U = Unit process.

Table 4. Output data sources

Output Data	Qty	Unit	Dataset	Database
Waste wood biomass	9.52	kg	Waste wood, untreated {GLO}| treatment of waste wood, untreated, open dump, dry infiltration class (100mm) | Cut-off, U	Ecoinvent 3
Biomass waste	0.7	kg	Biowaste, garden waste {FR}| treatment of garden biowaste, home composting in heaps | Cut-off, U	Ecoinvent 3

GLO = Global; FR = France; U = Unit process.

trituration), and 3 GLO datasets (dry leaves, diesel fuel energy, and wood biomass waste). In the production of twigs and leaf pellets, the ID dataset used is relatively small and dominated by other datasets; this is due to the limited inventory datasets in Indonesia. The determination of databases is done by considering the allocation and availability of data based on the process and geographical aspects. Most of the databases used are from Ecoinvent 3 with a 'cut-off' allocation model, which is a common approach in life cycle analysis to manage material flows in multi-output systems.

In the production process of biopellets made from twig and leaf organic waste, input and output inventory data are presented in Table 4, which shows that the production capacity for twig biopellets is 9.85 kg/batch and leaf biopellets is 9.9 kg/batch. The production of pellets from twigs and leaves requires varying amounts of raw materials, 32.50 kg, and 26.12 kg, respectively, which are obtained from the Taman Semangat IPB landfill as the starting material. After sorting and drying process for 12 hours, the weight of the raw material shrinks, resulting in 31.65 kg of dry twigs and 25.48 kg of dry leaves. The process of preparing raw materials for twigs is almost the same as for leaves; the only thing that distinguishes it is the process of chopping twigs, which uses electrical energy due to differences in the characteristics and material structure of twigs and leaves. In the chopping process, the dry twigs are cut into small parts so that the weight is reduced from 31.65 kg to 31.15 kg. This process takes 1.35 hours with a total electrical energy consumption of 0.89 kWh.

Furthermore, Table 5 shows in the crushing or grinding process, 31.15 kg of chopped branches were crushed for 1.16 hours with a diesel energy consumption of 75.24 MJ, resulting in a final weight of 21.16 kg. Meanwhile, dry leaves that had an initial weight of 25.48 kg were crushed for 0.25 hours with a diesel energy consumption of 15.96 MJ, resulting in a final weight of 24.78 kg. Then, in the process of pressing twig pellets using 12 kg of twig powder using a pelletizer machine for approximately 3 hours with a total electrical energy of 2.20 kWh for twig pellets and 2.25 kWh for leaf pellets. Pellets produced from dried twigs and leaves show differences in appearance characteristics. Twig pellets tend to be dark brown close to black, while leaf pellets have a lighter brown colour, as shown in Figure 5. The data obtained from this production process is then used for environmental impact analysis with SimaPro software for sustainability analysis to optimize the efficiency of the production process and reduce the environmental footprint of the pellets produced.

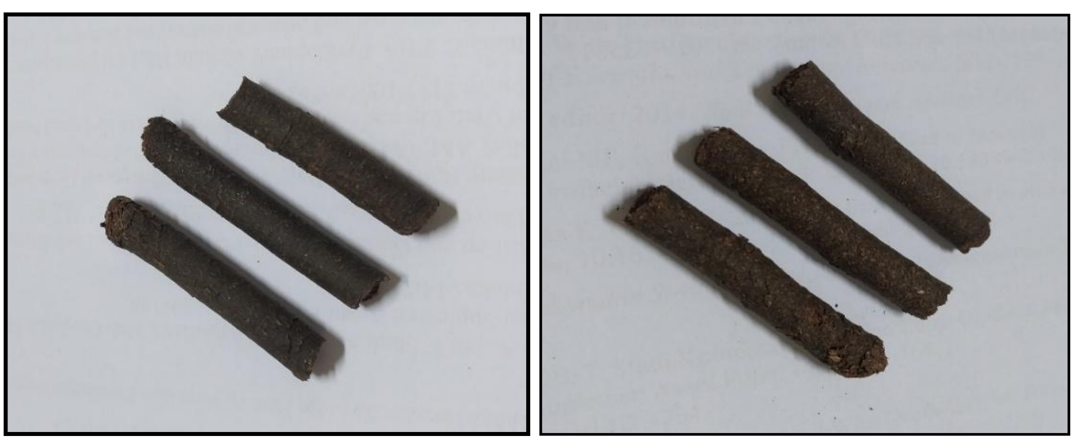


Figure 5. (a) Twig pellets; (b) Leaf pellets

Table 5. Overall inventory analysis for biopellet production

Process sub-stages	Inventory data	Per batch	Unit
Drying and cleaning of twigs and leaves	Twigs	32.5	kg
	Leaves	26.12	kg
	Human labour	12	h
	Dry twigs	31.65	kg
	Water vapours	0.85	L
	Dry leaves	25.48	kg
	Water vapours	0.64	L
Material chopping	Dry twigs	31.65	kg
	Human labour	1.6	h
	Electrical energy of chopper machine	0.89	kWh
	Twig cuttings	31.15	kg
	Biomass waste	0.5	kg
Material grinding	Twig cuttings	31.15	kg
	Human labour	1.2	h
	Diesel fuel	75.24	MJ
	Dry leaves	25.48	kg
	Human labour	0.25	h
	Diesel fuel	15.96	MJ
	Twig trituration	21.16	kg
	Leaves trituration	24.78	kg
	Biomass waste	9.72	kg
Biopellet pressing	Twig trituration	12	kg
	Human labour	3.15	h
	Electrical energy of pelletizer machine	2.2	kWh
	Leaves trituration	12	kg
	Human labour		h
	Electrical energy of Pelletizer	2.25	kWh
	Twig pellets	9.85	kg
	Leaves pellets	9.9	kg
Drying of biopellets	Twig pellets before	9.85	kg
	Leaves pellets before	9.9	kg
	Drying duration	4	h
	Dry twig pellets	8.47	kg
	Water vapours	1.38	L
	Dry leaves pellets	7.15	kg
	Water vapours	2.75	L

3.2. Environmental Impact Analysis

The results of the characterization analysis that has been carried out show the environmental impact assessment results on the life cycle of organic waste-based pellets. Each total environmental impact was calculated using SimaPro 9.5.0.2 software by adding all inventories through the processing menu.

In Table 6, the results of the characterization analysis of the total environmental impact of the entire life cycle of each process stage per kg for twig pellets and leaf pellets. Twig and leaf-based pellet production is a sustainable energy solution that produces lower CO_2 emissions compared to conventional fuels. Biopellets made from twigs have a GWP value of 3.05 kg CO_2-eq/kg of pellet, while pellets made from leaves have a GWP value of 0.54 kg CO_2-eq/kg, as presented in Table 6. Biopellets made from twigs have a SOD value of 1.3×10^{-6} kg CFC11-eq/kg of pellet, while pellets made from leaves have a SOD value of 1.35×10^{-7} kg CFC11 eq/kg, as presented in Tables 6. The twig pellets have a TAC value of 0.011 kg SO_2-eq/kg pellet production, while in the production of leaf pellets, the TAC value is 0.0018 kg SO_2-eq/kg as presented in Tables 6.

Table 6. Environmental impact characterization analysis per kg of biopellets

Impact category	Unit	Total/kg Biopellets	
		Twig pellets	Leaves pellets
Global warming potential (GWP)	kg CO_2-eq	3.05	0.54
Stratospheric ozone depletion (SOD)	kg CFC11-eq	1.3 x 10^{-6}	1.35 x 10^{-7}
Terrestrial acidification (TAC)	kg SO_2-eq	0.011	0.0018
Freshwater eutrophication (FEU)	kg P-eq	0.005	0.0006
Human carcinogenic toxicity (HCT)	kg 1.4-DCB-eq	0.538	0.13

In Tables 6, the overall environmental impact of FEU is also presented in the production of 0.005 kg P-eq/kg twig pellets and 0.0006 kg P-eq leaf pellets, after which the HCT impact on the entire production process of 0.538 kg 1.4-DCB-eq/kg twig pellets and 0.130 kg 1.4-DCB-eq/kg leaf pellets as presented in Table 5. To understand the environmental impacts of pellet production based on organic waste in the form of twigs and leaves, a Life Cycle Assessment (LCA) analysis was conducted.

Figures 6 summarizes the percentage contribution of various inputs and processes to different environmental impact categories, such as climate change (GWP), ozone layer depletion (SOD), and others. The results of this research will be the basis for identifying areas that require improvement and optimisation, so as to make a significant contribution to policy development at IPB University. To achieve this, integration of research results with institutional policies is required, which can be realised through the implementation of a structured waste management programme, the use of environmentally sound technology, and active participation of students and staff in waste sorting activities.

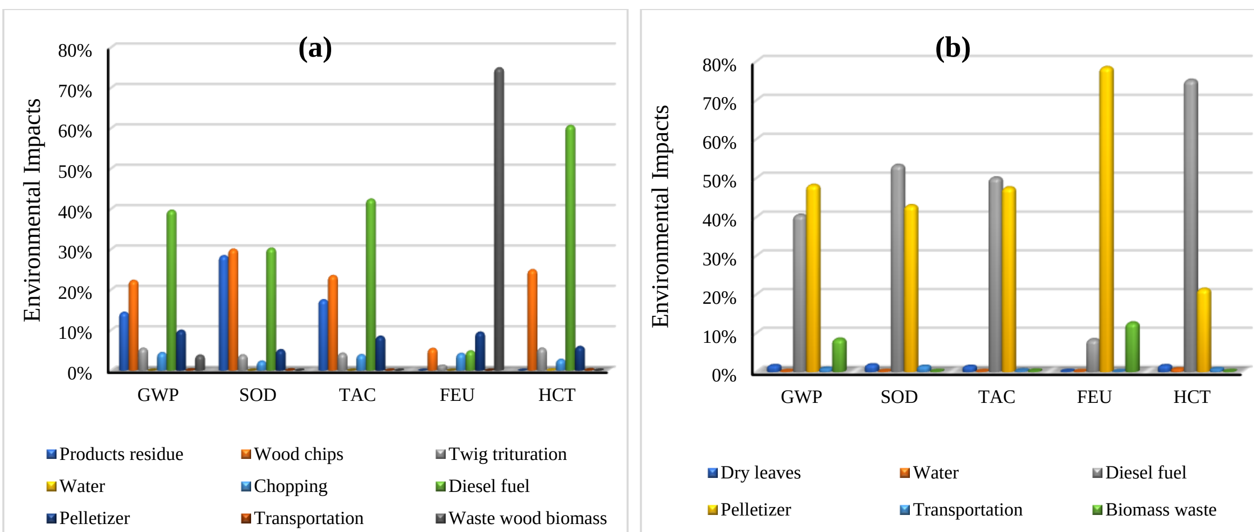


Figure 6. Environmental impacts of biopellet production based on production steps: (a) Twig pellet, (b) Leaves pellet

3.3. Global Warming Potential (GWP)

The environmental impact of the production of twig-based pellets is mainly due to the grinding process of the material using diesel-fueled diesel engines as well as the presence of small pieces of twigs. The GWP contribution of each of these factors is 40% (Figure 7a) equivalent to 1.21 kg CO_2-eq and 22% (Figure 7a) or equivalent to 0.68 kg CO_2-eq. Meanwhile, the environmental impact of leaf-based pellet production is caused by the pelletization process that uses electrical energy as well as the material grinding process. The GWP contribution of each of these factors is 48% (Figure 7b) equivalent to 0.265 kg CO_2-eq and 41% (Figure 7b) or equivalent to 0.222 kg CO_2-eq. Based on the LCA analysis in SimaPro on twig pellets, each solar energy produced in the grinding process contributes 1.21 kg CO_2-eq to GWP. The dominant emissions released are carbon dioxide (fossil) and methane (fossil), at 1.06 kg CO_2-eq and 0.131

kg CO_2-eq, respectively. In addition, 1 kg of small pieces of chopped twigs contributed 0.68 kg CO_2-eq to GWP, with the dominant emissions released being carbon dioxide (fossil) and methane (fossil), at 0.57 kg CO_2-eq and 0.09 kg CO_2-eq, respectively.

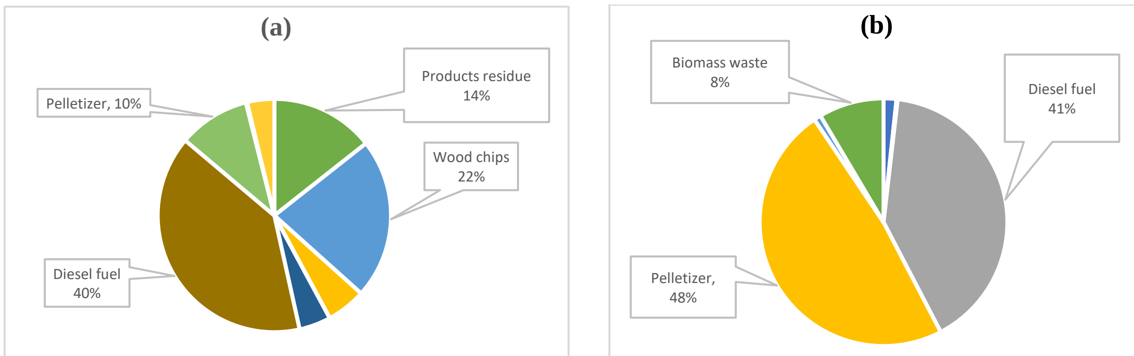


Figure 7. Major contributors of GWP from biopellets production: (a) Twig pellets; (b)Leaves pellet

In addition, twigs as the main raw material for pellets can increase GWP if not managed sustainably. LCA analysis with SimaPro showed that 1 kg of twigs contributed to a GWP of 0.439 kg CO_2, with major emissions of carbon dioxide (fossil) 0.413 kg CO_2 and nitrous monoxide 0.0099 kg CO_2. The pelletization process using electrical energy also contributes to GWP, where 1 kg of twig pellets produces 0.303 kg CO_2, with major emissions of carbon dioxide (fossil) 0.29 kg CO_2 and nitrous monoxide 0.00177 kg CO_2.

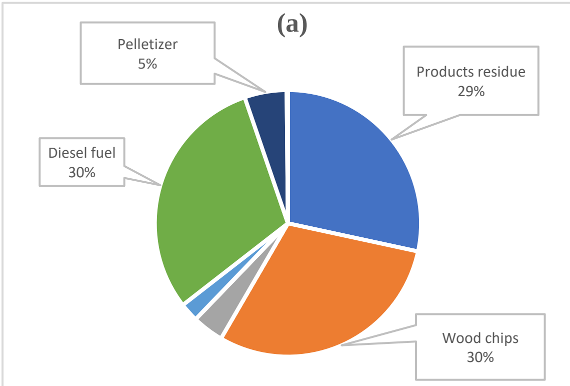
The pelletization of leaf pellets contributed 0.265 kg of CO_2eq with the dominant emissions being carbon dioxide (fossil) at 0.254 kg CO_2-eq and methane (fossil) at 0.008 kg CO_2-eq. In addition to pelletization, the pellet leaf pelletization process contributed to a GWP of 0.222 kg CO_2-eq with the dominant emissions being carbon dioxide (fossil) at 0.19 kg CO_2-eq and methane (fossil) at 0.092 kg CO_2-eq. In addition, leaf as In addition, biomass waste and material grinding processes contribute to GWP, with the main emissions being Carbon dioxide (fossil) at 0.017 kg and 0.1952 kg CO_2-eq, respectively.

The difference in GWP contribution between twig- and leaf-based pellets stems from their material properties. Twigs, with higher lignocellulose content, require more intensive grinding due to their dense structure, thus increasing diesel consumption which contributes to the high GWP. In contrast, leaf-based pellets have a lower lignin content, thus requiring higher compaction pressure, which leads to electricity use and contributes to high GWP, this is similar to previous studies conducted by Laschi *et al*. (2016) and Hamedani *et al*. (2019).

Based on the results of research related to wood-based pellet production by Chen *et al.* (2019), show that the transportation process of wood raw materials contributes significantly to the increase in CO_2 emissions compared to other processes. However, this condition is different from the production of twig and leaf-based pellets in the 267 ha IPB Dramaga Campus area, where transportation is not a major factor contributing to emissions. This is due to the relatively short distance, about 12 km, from several waste collection points to the final disposal site. Thus, transportation in this production activity does not contribute significantly to the increase in CO_2 emissions.

3.4. Stratospheric Ozone Depletion (SOD)

The contribution of SOD in production twig pellets is 1.3×10^{-6} kg CFC11-eq/kg, and in leaf pellets, the SOD contribution is 2.42×10^{-7} kg CFC11-eq. In twig pellets, the grinding of materials and the use of small pieces of twigs caused significant environmental impacts (Figure 8a); the crushing of materials and the use of small pieces of twigs contributed to SOD of 3.93×10^{-7} kg CFC11-eq/kg of pellets. Meanwhile, for leaf pellets, material grinding contributed to SOD by 53% (Figure 8b). In the twig pellets, based on the LCA analysis in SimaPro, the grinding process involving diesel fuel contributed to stratospheric ozone depletion of 3.9×10^{-7} kg CFC11-eq with the dominant emissions being nitrous monoxide at 3.78×10^{-7} and methane and bromotrifluoro at 1.34×10^{-8} kg CFC11-eq.



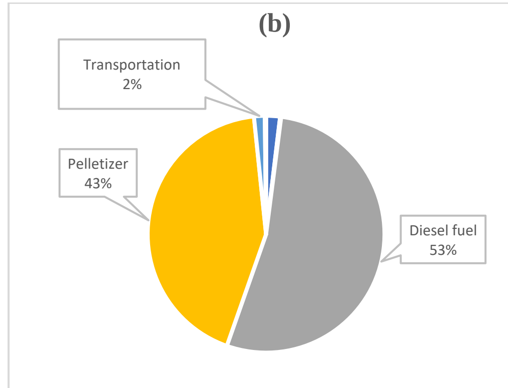


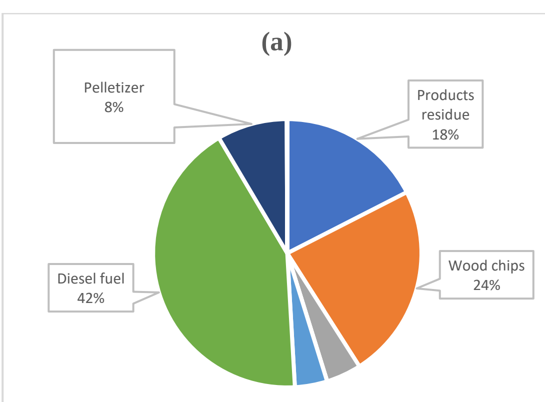
Figure 8. Major SOD contributors for biopellet production: (a) Twig pellets; (b) Leaves pellet

In addition, small twig pieces also contribute to stratospheric ozone depletion by 3.9×10^{-7} with dominant emissions of nitrous monoxide by 3.83×10^{-7} kg CFC11-eq and methane and bromotrifluoro (halon 1301) by 4.27×10^{-9} kg CFC11-eq. The unchopped twigs also contributed to SOD, with the main emissions being methane bromotrifluoro (Halon 1301) at 4.72×10^{-9} kg CFC11-eq and nitrous monoxide at 4.83×10^{-7} CFC11-eq. Similarly, the pelletization process produces dominant emissions of dinitrogen monoxide at 6.53×10^{-8} kg CFC11-eq and methane bromotrifluoro (Halon 1301) at 1.1×10^{-9} kg CFC11-eq. The LCA analysis in SimaPro for leaf pellets showed that the grinding process also contributed 7.22×10^{-8} kg CFC11-eq/kg pellets. The dominant emissions generated are nitrous monoxide at 2.98×10^{-10} kg CFC11-eq and methane emissions, bromotrifluoro at 6.88×10^{-8} kg CFC11-eq on stratospheric ozone depletion. In addition, the compaction and transportation processes contribute to SOD, with the main emissions being dinitrogen monoxide at 5.72×10^{-8} kg CFC11-eq kg and 6.05×10^{-9} kg CFC11-eq, respectively.

3.5. Terrestrial Acidification (TAC)

The soil acidification contribution (TAC) in the production of twigs and leaf pellets is presented in Figures 9. The TAC in twig pellets was 0.011 kg SO_2-eq/kg pellets, with a significant environmental impact coming from the material grinding process, which contributed 42% (Figure 9a). Based on the LCA analysis in SimaPro, the dominant emissions released are nitrogen oxides at 0.003 kg SO_2-eq and sulfur dioxide at 0.001 kg SO_2-eq. The diesel used as diesel fuel in the material refining process contains sulfur, which can produce sulfur dioxide. If released in large quantities, these emissions have the potential to cause acid rain, which impacts soil quality and disrupts ecosystems.

In addition, twig waste contributes to the Total Acidification Potential (TAC), based on LCA in SimaPro with the main emissions being ammonia (0.00015 kg SO_2-eq), nitrogen oxides (0.00129 kg SO_2-eq), and sulfur dioxide (0.00138 kg SO_2-eq). Chopped twigs also contribute, with the dominant emission being nitrogen dioxide at 0.00109 kg



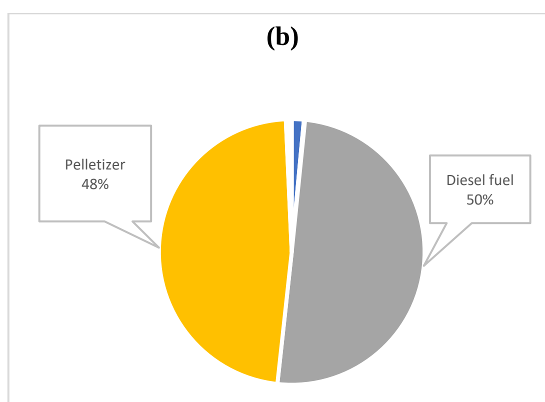


Figure 9. (a). Major TAC of twig pellets contributor; (b). Major TAC of leaves pellet contributor

SO_2-eq. The pelletization process also contributes to emissions, with sulfur dioxide as the main component at 0.00017 kg SO_2-eq. Meanwhile, the TAC contribution of leaf pellets was 0.002 kg SO_2-eq per kg of pellets, with the largest impact coming from the material grinding process, which contributed 38% (Figure 9b) per kg of pellets. The material grinding process in twig pellets contributes to the TAC of 0.005 kg SO_2-eq. In the case of leaf pellets, the crushing process contributes to a TAC of 0.0008 kg SO_2eq, with the dominant emissions released being sulfur dioxide of 0.00033 kg SO_2-eq and nitrogen oxide emissions of 0.00058 kg SO_2-eq.

3.6. Freshwater Eutrophication (FEU)

The contribution of freshwater eutrophication (FEU) to the production of twig pellets can be seen in Figure 10a. The contribution of FEU as phosphorus equivalent is 0.005 kg P-eq per kg of twig pellets. The significant environmental impact is caused by the final product of the twig pellet chopping and grinding process, which is wood biomass waste with a contribution percentage of 75% (Figure 10a) or about 4.38×10^{-3} kg P-eq per kg of twig pellets to FEU.

Based on the LCA analysis in SimaPro for twig pellets, every 1 kg of woody biomass waste that is not treated appropriately or sustainably can contribute to an FEU of 0.004 kg P-eq. The dominant emissions from woody biomass waste left over from processing twig pellet production include Chemical Oxygen Demand (COD) of 0.003 kg P-eq and phosphate of 8.46×10^{-6} kg P-eq. Wood biomass waste increases COD due to the high organic compounds contained in it which can cause a lot of oxygen to break down. In addition, based on the LCA analysis in Simapro, the process of compaction and grinding of materials contributes to FEU, with the main emissions generated in the form of Phosphate of 0.0005 kg P-eq and 0.000158 kg P-eq.

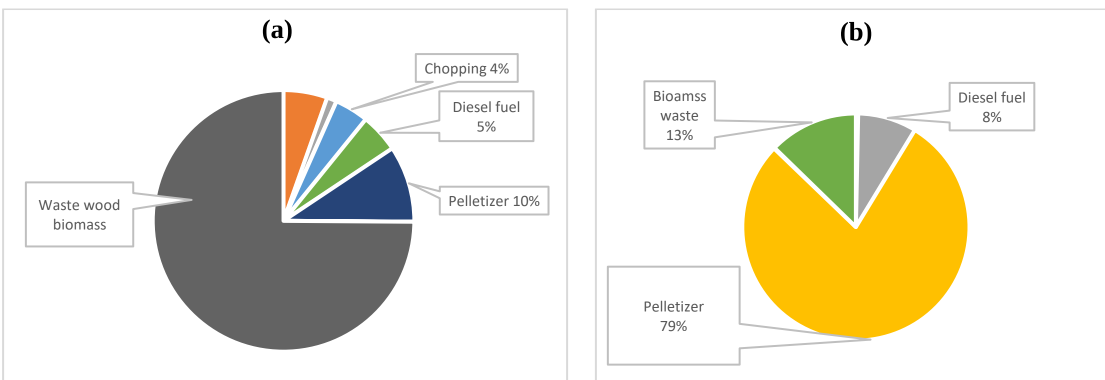


Figure 10. Major FEU contributor for biopellet production: (a) Twig pellets; (b) Leaves pellet

Meanwhile, the contribution of FEU in leaf pellets was 0.0006 kg P-eq per kg pellets. The significant environmental impact of pellet production on FEU was caused by pelletization using electrical energy by 79% (Figure 10b) or about 4.84×10^{-4} kg P-eq/kg. Based on the LCA analysis in SimaPro for leaf pellets, the pelletization process contributes to TAC of 4.84×10^{-4} kg P-eq, with the dominant emissions released in the form of phosphate of 0.00048 kg P-eq and Chemical Oxygen Demand (COD) of 1.64×10^{-6}. In addition, biomass waste and the material grinding process contribute to FEU, with the main emissions being at 1.21 kg and 0.03 kg, respectively.

3.7. Human Carcinogenic Toxicity (HCT)

The contribution of carcinogenic human toxicity (HCT) in the production of twigs and leaf pellets can be analyzed based on Figures 11a and 11b. In twig pellets, the HCT value reached 0.538 kg 1.4-DCB-eq/kg of pellets, with the material grinding process as the main contributor to the environmental impact. This process contributed 61% or approximately 0.326 kg 1.4-DCB-eq to the total HCT value (Figure 11a). Based on the LCA analysis in SimaPro, the material grinding process in twig pellets contributes quite a bit compared to other processes, which is 0.538 kg 1.4 DCB-eq per kg of pellets. The dominant emissions released are chromium (VI) and formaldehyde with respective values of 0.323 kg 1.4-DCB-eq and 4.65×10^{-5} kg 1.4 DCB-eq. In addition, based on the LCA analysis using SimaPro,

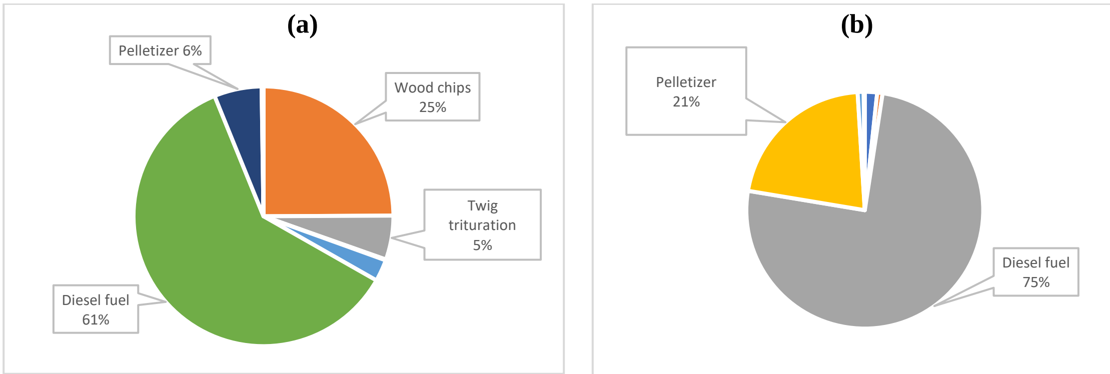


Figure 11. Major HCT contributors for biopellet production: (a) Twig pellets; (b) Leaves pellet

small pieces of branches and compaction of materials contribute to HCT, with the main emissions being Chromium (VI) at 1.21 kg and 0.03 kg, respectively.

Meanwhile, in leaf pellets, the HCT contribution is lower, at 0.129 kg 1.4-DCB eq/kg pellets, with the largest impact coming from the material grinding process, which contributes 75% or about 0.097 kg 1.4-DCB-eq to the total HCT value and with the dominant emission contribution in the form of Chromium (VI) 0.0594 kg 1.4-DCB-eq to (Figure 11b). In addition, pelletization also contributes to HCT of 0.0278 kg with the dominant emission of Chromium (VI) 0.0263 kg 1.4-DCB-eq/kg.

The high HCT value in the material grinding process, especially in twig pellets, is due to the use of diesel engines fueled by diesel. Diesel combustion in diesel engines produces emissions of harmful compounds such as polyaromatic hydrocarbons (PAHs), benzene, formaldehyde, and fine particulate matter ($PM_{2.5}$), which are known to be carcinogenic. These compounds can be released into the environment and accumulate in soil, air, and water, increasing potential human health risks from long-term exposure (Yuda & Assomadi, 2023). In addition, heavy metal emissions from diesel combustion may also contribute to increased environmental toxicity, compounding the impact of HCT in the pellet's life cycle.

4. CONCLUSION

The environmental impact of twig pellet production is, on average, higher than that of leaf pellets. For each kg of twig pellets contribute to global warming by 3.05 kg CO_2-eq, SOD by 1.3×10^{-6} kg CFC11-eq, TAC by 0.011 kg SO_2-eq, FEU by 0.005 kg P-eq, and HCT by 0.538 kg 1.4-DCB-eq. Meanwhile, per kg of leaf pellets contributed to global warming by 0.54 kg CO_2-eq, SOD by 1.35×10^{-7} kg CFC11-eq, TAC by 0.0018 kg SO_2-eq, FEU by 0.0006 kg P-eq, and HCT by 0.130 kg 1.4-DCB-eq. The majority of the contribution to the environmental impacts of both pellet production processes comes from the grinding stage, which utilizes diesel fuel as the main energy source. The benefits of this research are expected to reduce the volume of organic waste, reduce greenhouse gas emissions, and produce renewable energy products that are environmentally friendly. Based on the result, the production of twig pellets has a higher environmental impact than that of leaf pellets, especially at the grinding stage, which used diesel fuel. For this reason, further research can focus on optimizing the grinding process, conducting LCA with more system boundaries, and exploring other organic wastes for sustainable solutions. In addition, research on improving the quality of pellets and developing supportive policy can increase the use of pellets as an environmentally friendly renewable energy source.

REFERENCES

Buchholz, T., Gunn, J.S., & Saah, D.S. (2017). Greenhouse gas emissions of local wood pellet heat from northeastern US forests. *Energy*, ***141***(December 2017), 483–491. https://doi.org/10.1016/j.energy.2017.09.062

Çetinkaya, B., Erkent, S., Ekinci, K., Civan, M., Bilgili, M.E., & Yurdakul, S. (2024). Effect of torrefaction on fuel properties of biopellets. *Heliyon*, ***10***(2), e23989. https://doi.org/10.1016/j.heliyon.2024.e23989

Chen, C.X., Pierobon, F., & Ganguly, I. (2019). Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix. *Sustainability*, ***11***(5), 1278. https://doi.org/10.3390/su11051278

Farobie, O., Amrullah, A., Bayu, A., Syaftika, N., Anis, L.A., & Hartulistiyoso, E. (2022). In-depth study of bio-oil and biochar production from macroalgae *Sargassum* sp. via slow pyrolysis. *RSC Advances*, ***12***(16), 9567–9578. https://doi.org/10.1039/d2ra00702a

Hamedani, S.R., Colantoni, A., Gallucci, F., Salerno, M., Silvestri, C., & Villarini, M. (2019). Comparative energy and environmental analysis of agro-pellet production from orchard woody biomass. *Biomass and Bioenergy*, ***129***(August), 105334. https://doi.org/10.1016/j.biombioe.2019.105334

Hernández, D., Fernández-Puratich, H., Rebolledo-Leiva, R., Tenreiro, C., & Gabriel, D. (2019). Evaluation of sustainable manufacturing of pellets combining wastes from olive oil and forestry industries. *Industrial Crops and Products*, ***134***(November 2018), 338–346. https://doi.org/10.1016/j.indcrop.2019.04.015

IEA. (2023). *Greenhouse, Gas Emissions from Energy Data Explorer – Data Tools*. https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer, 23. 12. 2024.

IPCC. (2014). *AR5 Climate Change 2014: Mitigation of Climate Change — IPCC*. https://www.ipcc.ch/report/ar5/wg3/, 23. 12. 2024.

Kementrian LHK RI. (2021). *Program Kinerja Perusahaan dalam Pengelolaan Lingkungan Hidup (PROPER)*. Kementrian Lingkungan Hidup dan Kehutanan RI.

Kumaat, E.J., Manembu, I.S., Mambu, S.M., & Mangindaan, G.M.C. (2023). Sustainable campus through organic waste management program implementation. *Journal of Sustainability Perspectives*, ***3***(2023) 581–586. https://doi.org/10.14710/jsp.2023.21647

Laschi, A., Marchi, E., & González-García, S. (2016). Environmental performance of wood pellets' production through life cycle analysis. *Energy*, ***103***(2016), 469–480. https://doi.org/10.1016/j.energy.2016.02.165

Martín-Gamboa, M., Marques, P., Freire, F., Arroja, L., & Dias, A.C. (2020). Life cycle assessment of biomass pellets: A review of methodological choices and results. *Renewable and Sustainable Energy Reviews*, ***133***(August). https://doi.org/10.1016/j.rser.2020.110278

Martins, F., Felgueiras, C., Smitkova, M., & Caetano, N. (2019). Analysis of fossil fuel energy consumption and environmental impacts in European countries. *Energies*, ***12***(6), 1–11. https://doi.org/10.3390/en12060964

Ruiz, D., San Miguel, G., Corona, B., & López, F.R. (2018). LCA of a multifunctional bioenergy chain based on pellet production. *Fuel*, ***215***(January 2016), 601–611. https://doi.org/10.1016/j.fuel.2017.11.050

Saleem, M. (2022). Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. *Heliyon*, ***8***(2), e08905. https://doi.org/10.1016/j.heliyon.2022.e08905

Saosee, P., Sajjakulnukit, B., & Gheewala, S.H. (2020). Life cycle assessment of wood pellet production in Thailand. *Sustainability*, ***12***(17), 1–22. https://doi.org/10.3390/su12176996

Sgarbossa, A., Boschiero, M., Pierobon, F., & Zanetti, M. (2020). Comparative life cycle assessment of bioenergy production from di different wood pellet supply chains. *Forest*, ***11***(11), 1127. https://doi.org/10.3390/f11111127

Siregar, K., Supriyanto, Setiawan, A.A.R., Wiloso, E.I., Sholihati., Miharza, T., & Sofia, I. (2020). IDN-LCI: The conceptual framework of the Indonesian life cycle inventory database to support the life cycle assessment. *IOP Conference Series: Earth and Environmental Science*, ***542***(1). https://doi.org/10.1088/1755-1315/542/1/012044

Supriyanto., Pratama, A.N., Erniati., & Sucahyo, L. (2025). Life cycle assessment of melon (*Cucumis Melo* L) production in tropical greenhouse, Indonesia. *Jurnal Teknik Pertanian Lampung*, ***14***(1), 226-239. http://dx.doi.org/10.23960/jtep-l.v14i1.226-239

Yuda, A., & Assomadi, A.F. (2023). Kajian dampak emisi udara pada produksi minyak bumi di perusahaan "A" menggunakan metode life cycle assessment (LCA). *Jurnal Purifikasi*, ***21***(2), 52–60. https://doi.org/10.12962/j25983806.v21.i2.440